RM L55E09b

RESEARCH MEMORANDUM

REDUCTION OF HYDRODYNAMIC IMPACT LOADS

FOR WATERBORNE AIRCRAFT

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON

July 6, 1955
Declassified May 8, 1957

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

Recent NACA research aimed at the reduction of water loads on both hull and hydro-ski-equipped seaplanes is presented. It is shown that hull loads can be reduced by proper trim programming from elevator action and by use of high dead rise. For the hydro-ski-equipped seaplanes, loads are shown to be reduced by a decrease of ski beam or length and by mounting the ski on either conventional shock struts or on a new type of frequency-discriminating shock strut.

INTRODUCTION

The rough-water loads problem is one of the chief factors limiting greater use of the seaplane. Various means exist for reducing these loads such as control techniques, hull modifications, and auxiliary devices, particularly hydro-skis. The present paper summarizes recent NACA research in these fields of water-load reduction. Earlier loads work on hydro-ski-equipped seaplanes has been reported and is summarized in reference 1 along with a fairly complete reference bibliography.

The water-loads investigations covered in this paper are divided into two general groups, the first applying to the hull-type seaplane and the second, mainly to the hydro-ski-equipped seaplane. Under the heading of hulls, attitude control by elevator action and variations in bottom cross section (namely, dead rise) are considered. Under hydro-skis, consideration is given to beam loading (hull loading based on the beam or width), plan-form proportions, and types of shock-strut mountings. The shock mountings include the translating- and trimming-ski types and a frequency-discriminating oleo called the low-band-pass shock strut. A bibliography of related work is included.

HULLS

Attitude Control

Model experiments.- The loads encountered in a water take-off or landing depend on the manner in which the airplane attitude or trim is varied during the run. In the past, pilots have exerted some trim control during water operations. Recently, an attempt has been made to evaluate the amount of load alleviation possible by the use of various forms of such trim programming. In figure 1 is shown the effect of three different types of trim control, namely, fixed elevators, fixed trim, and automatically controlled elevators, on hull loads experienced in landings. These results were obtained in an experimental program conducted in the Langley Hydrodynamics Division with a model flying boat landing in oncoming waves. All the experimental waves discussed in this paper were approximately sinusoidal in shape and occurred in a single train. The same critical wave condition was used throughout this trim-control investigation. Each point plotted gives the relative maximum vertical acceleration experienced during one landing and thus represents several impacts, since each landing or take-off consists of a series of bounces from wave to wave. Relative values of the vertical acceleration are shown on this and succeeding figures because the magnitudes of the loads do not necessarily represent those encountered in open-sea operations. The trends, however, are thought to be similar.

The first cluster of points at the left of figure 1 represents recommended Navy practice for the average pilot in which the elevators are held fixed with the nose high. The spread of the data in this figure results from contacting at different positions on the waves at various flight conditions. The second cluster of points representing the fixed-trim condition, which to date has only been realized in laboratory tests, shows a possible reduction of 40 percent below the fixed-elevator case when the highest values of acceleration are compared. Possibly the fixed-trim condition could be achieved in practice by means of water elevators or vertical rockets. The short horizontal lines represent the acceleration levels exceeded during 10 percent of the landings. These levels are believed to give more realistic comparisons from a statistical point of view and are seen to yield the same qualitative conclusions obtained by comparing maximum accelerations. The third cluster of points represents an attempt to approach, as closely as possible, the fixed-trim condition in an actual flying boat by means of automatic elevator control. The control mechanism utilized for this test consisted of a combination of a trim-displacement control, which actuated the elevators to oppose a change in attitude, and a gyro-rate control, which actuated the elevators to oppose a trimming velocity of the flying boat. The elevator deflection speeds approximated conventional autopilot control rates. This control system gave a reduction in maximum vertical acceleration of 20 percent below the fixed-elevator case as shown, and an even greater

reduction in angular acceleration of 40 percent (not shown). It may be concluded from this material that proper programming of take-off and landing attitudes of flying boats can substantially reduce maximum water impact loads.

Narrow-body trimming theory.- It may be of some interest to note that there are theoretical methods available for determining the effects of different kinds of trim control on loads. In order to study trim-control techniques, the trimming case must first be defined accurately. During a seaplane take-off or landing the flight conditions of the airplane as it leaves one wave greatly influence the contact conditions on the next wave; thus the complete time history of the motions during any impact must be known. Previously, fixed-trim theory (ref. 1) was available for calculating maximum impact force, which was extended for the wide-float case to the entire time history (ref. 2). More recently, a quasi-steady trimming theory was developed to cover impact and planing of narrow hulls or hydro-skis undergoing pitching rotation. This theory is based on a dynamic-camber concept in which a pitching flat plate immersed in a streaming fluid is assumed to be replaced by a fictitious cambered plate fixed in space, for which the degree of camber at any instant is related to the pitching velocity of the original flat plate.

In order to evaluate the effects of trimming motion during impact, this new theory is compared with the fixed-attitude narrow-body theory in figure 2. This figure shows a sample load time history of a rough-water impact of a large narrow flying boat. The solid line represents the dynamic-camber theory, and the line of long dashes represents the fixed-attitude theory. It appears from this figure that for the case considered the maximum accelerations are in fair agreement, whereas during the remainder of the time histories the disagreement is increased. It should be borne in mind, however, that the angular motions are substantially different for the two theories. This means that, for a single impact for which the initial conditions are known, approximate calculations of maximum load by means of the fixed-attitude theory might suffice. However, since an actual seaplane take-off or landing involves the interplay of air and water forces through a sequence of impacts any of which can be the worst one, calculations of complete time histories of water operations where the integrated effects of all the variables are critical, or in which pitching motion is important, will require the more exact theory which takes into account the effects of angular rotation. The line of short dashes represents an intermediate type of approximation which ignores the effects of rotation on the load distribution but extends the fixed-attitude theory by taking into account the velocity vector contributed by the pitching motion. This theory is probably adequate for a fairly large range of condition.

Cross Section

The degree of load alleviation attainable by sharpening up the bottom of the hull, that is, increasing its dihedral or dead rise in nautical terminology, is now considered. Although high dead rise, while reducing impact loads, is accompanied by increased water drag during take-off, this drag penalty is partially offset by the increased thrust available with modern engines.

The results of an experimental investigation of effects of dead rise are shown in figure 3. Tests were made with a dynamic scale model of a high-speed flying boat landing on waves 4 feet high and ranging from 180 feet to 320 feet in length scaled to full size. The data obtained in this investigation were cross-plotted to yield the relative values of maximum landing acceleration for a constant hull width or beam. From this figure it is evident that, for the range of wave length used, the maximum load decreases almost linearly with increasing dead rise, at least up to dead-rise angles of 60° for flying boats in free flight. This downward trend of load with increasing dead rise follows theoretical and experimental predictions based on fixed-trim landings in smooth water. It should perhaps be noted that some indications of directional instability for the 60° case occurred at low trims and are being investigated further. The effect of wave length is seen to decrease at the higher dead rises for the constant wave height tested, and, as may have been expected from geometric considerations involving the ratio of hull to wave length, the intermediate wave length of 230 feet is seen to give the highest loads. It may be concluded from these tests, therefore, that the high dead rises are very effective in reducing rough-water loads and in addition possess satisfactory hydrodynamic qualities with respect to spray and stability.

HYDRO-SKIS

Beam Loading

The next topic under consideration is the study of load alleviation by means of hydro-skis. The first hydro-ski parameter considered is the beam-loading coefficient usually denoted by C_Δ. This parameter is somewhat similar to wing loading in that it relates the weight of the aircraft to the dimension of the body. In the aerodynamic case, the entire area of the wing is significant because it is always completely immersed in the fluid, whereas, in the hydrodynamic case, beam loading relates the aircraft weight to the hydro-ski beam only because the wetted length of the ski bottom varies throughout the impact.

The effect of beam loading on water loads is illustrated in figure 4 which was constructed from the results of several hundred landings

of flat rectangular plates in the Langley impact basin. The flat plate was selected since it was believed to approximate the hydro-ski which usually has a fairly low dead rise. The sketch at the top of the figure identifies the model mass m, beam b, trim τ, initial flight-path angle γ, resultant velocity V, and water density ρ. The ranges of variables tested include beam-loading coefficients from 1 to 134, trim angles from 3° to 45°, and flight-path angles from 2° to 22°. When these data are plotted in the nondimensional form shown in this figure, all the data condense within the envelope included by the shaded area. If dead-rise data were plotted in this figure, such data would probably group below the flat-plate data, the degree of separation depending on the dead rise and possibly also on the beam loading tested. From this plot we can see that the impact lift coefficient C_L can be approximated by a simple linear function of the product of the flight-path angle at contact γ times the cube root of the beam-loading coefficient C_{Δ}. Since an increase in beam loading is associated with either an increase in weight or a reduction in beam, it is evident that, when the nondimensional parameters are defined, the maximum impact force varies directly with the beam and the cube root of the weight. Thus, it turns out that higher beam loadings reduce impact accelerations although they are usually associated with more severe spray conditions. The spread of the data in the envelope results principally from the effect of trim. We may conclude from the wide ranges of the variables tested that for load estimation the trim effect can be neglected, the effect of flight path can be taken as a linear function, and the beam-loading effect can be closely represented by the cube-root function.

In order to estimate maximum impact force from this plot a straight line has been faired through the data, the equation of which yields the impact lift coefficient. (Note that γ is expressed in degrees in this equation.) The maximum impact force can be calculated from the equation for F_{MAX} also given in the figure. With this information the designer can approximate for his particular airplane the impact-load reductions possible through manipulation of weight, beam, and flight-path angle.

Plan Form

Reductions in impact acceleration can be achieved for the hydro-ski by increasing its beam loading as has been demonstrated. Another parameter investigated was the proportioning of the hydro-ski plan form. The plan-form investigation was carried out in the Langley tank no. 1 with a dynamic model of a hydro-ski-equipped flying boat. In these tests the model was landed on waves having a height of 4 feet and 4 different lengths. The initial conditions of impact were made as nearly alike as practicable.

Figure 5 illustrates the effect on loads of variations of the hydro-ski plan form pictured, where each point represents a considerable number of landings. The values plotted represent the accelerations exceeded for the ski in 10 percent of the landings relative to the acceleration for the hull alone. Only the length and width of the skis have been varied. The effect of ski length on loads is obtained directly from the line connecting the three skis of equal beam identified by the solid points. The load is seen to increase with ski length. Even though the beam of the hull was equal to the beam of the ski on the extreme left of figure 5, use of skis is seen to reduce the load greatly. The effect of beam can also be seen on this plot if the two models of almost equal length are compared; the narrower ski gives the smaller load as predicted by the previous figure on beam loading. From figure 5 the general conclusion drawn is that the smaller the ski length, or beam, the lower the load. Since too small a ski allows the hull to contact the water and receive large subsequent impacts, a compromise must be made between the ski area and the length of the strut supporting it. Too long a strut creates a take-off problem with respect to drag loads.

Theoretical considerations show that the beam should be more powerful than the length as a load-controlling parameter. The data shown here tend to substantiate the theory if the three upper hydro-skis at the left of the figure having lengths of roughly 19, $20\frac{1}{2}$, and $23\frac{1}{2}$ feet and which have the same plan-form area are considered. From these three points the load is seen to decrease even if the ski length increases. Since the increase in length for a given ski area must be accompanied by a proportional decrease in beam, the conclusion that the beam has the main effect on loads is verified.

Shock Mountings

Translating ski.- Water loads have been shown to be reduced by the use of hydro-skis. How additional load reductions could be achieved by mounting hydro-skis on shock struts has also been demonstrated in the past by means of theoretical calculations (ref. 3). Since that time, landing tests with dynamic scale models have been made in the tanks to verify these calculations for the translating type of shock mounting, as shown in figure 6. These experimental results are presented in reference 4. With this type of mounting, the ski is not permitted to trim relative to the seaplane during the impact. Figure 6 presents a typical load time history of one of these impacts for a rough-water landing of a large jet hydro-ski seaplane. The theory is represented by the lower solid line and the corroborating experimental data, by the circled points. As a matter of interest the load for the same seaplane landing at the same initial conditions but with the shock strut locked out of action is presented by the upper solid line. For this case the load reduction achieved by the shock strut is 40 percent.

Trimming ski.- In addition to the translating type of mounting, several other methods of shock-mounted hydro-skis have been considered. In one of these methods, the hydro-ski was allowed to trim relative to the aircraft during compression of the shock strut. A computational method has been evolved by utilizing the dynamic-camber theory mentioned earlier in this paper, which enables the loads on these trimming hydro-skis to be calculated. A typical load time history computed by this method is presented in figure 7 by the lower line, which represents a rough-water landing of a fighter aircraft equipped with pivoted shock-mounted hydro-skis. Comparisons were not made with the translating-ski case because the time histories are drastically different and depend on the values selected for the many independent parameters.

In order to estimate roughly the load reduction achieved by this pivoted-ski arrangement, the load for the same aircraft landing at the same initial conditions but with the shock strut locked out of action is presented by the upper line of figure 7. The load reduction for the pivoted ski is seen to be about 26 percent with the rate of application of loading somewhat reduced. Notice that area on this slide is proportional to vertical impulse or momentum change. Since the area under the trimming-ski curve is smaller than for the fixed-ski curve it may be concluded from this figure, and probably also from complete time histories for the preceding figure, that the vertical rebound velocity is reduced by the shock-strut action, which results in much milder initial conditions for the next impact. From a practical point of view, the pivoted-ski mounting has the advantage of keeping the bending moments which may produce serious frictional loads out of the shock strut.

Low-pass shock strut.- When a conventional oleo strut is used with the types of shock mountings considered, load reductions can be expected during rough-water operations as long as the bumps or waves encountered by the aircraft are long and smooth. For short steep bumps, however, especially at high speeds, conventional oleos tend to become quite rigid and transmit the full shock loads to the aircraft. In order to overcome this difficulty, a new type of filter-action oleo, the low-pass shock strut, was conceived. This strut tends to filter out the rapidly applied loads from steep bumps while acting as a conventional oleo for smooth hills or swells.

In figure 8 simplified versions of the conventional oleo at the left and the low-pass strut at the right are compared. Usually, the conventional oleo is equipped with a fixed metering pin which can vary the size of the orifice in the piston only as a function of the strut telescoping displacement. Thus, when the lower end of the strut is forced upward, the rate of flow of fluid up through this orifice, which regulates the applied force, is controlled only by the strut telescoping displacement. Since the load developed in the strut is proportional to the square of the telescoping velocity, the steeper the slope of the

bump encountered by the landing gear, the more rigid the strut becomes, until for very steep bumps it is practically a rigid bar. The low-pass strut, on the other hand, has a movable metering pin which varies the orifice size as a function of the rate of loading and which is actuated by a special frequency-sensitive piston in the control cylinder shown at the top of the strut. For very steep bumps, the rapid increase of pressure in the lower cylinder is communicated through the large-diameter tube shown at the left side of the strut, to the under side of the control piston. This piston snatches the metering pin upward opening wide the orifice, allowing the strut to telescope easily, and thereby reducing the load. For slowly applied loads of either small or large magnitude, the metering pin remains in the equilibrium position shown so that a conventional fixed orifice strut is approximated.

In order to assess the effectiveness of the low-pass strut as applied to seaplanes, the results of theoretical calculations which have been made for a hydro-ski seaplane operating in rough water are shown in figure 9.

This figure is concerned with the loads experienced during high-speed operation on a complex sea made up of small steep waves superposed on large swells. Both wave trains are sinusoidal in shape and oriented in the same direction. The hydro-ski is assumed to penetrate the water so that the actual waves can be considerably higher than the magnitudes shown in the lower figure, which represents the hydro-ski motion only. The upper figure shows that the conventional shock strut develops large loads for the high-frequency waves or in the region of the steep wave fronts, whereas the low-pass strut greatly reduces these loads.

CONCLUSIONS

The various methods which have been shown to be effective in reducing water loads are as follows:

For the flying boat,

Trimming restraint by elevator control
Increased bottom dead rise

For the hydro-ski,

Reduction of beam
Reduction of length
Shock mounting on conventional oleos for slowly applied loads and on low-pass shock struts for all rates of load application.

All these methods, either singly or in combination, can be used to effect load reductions during water operations.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 25, 1955.

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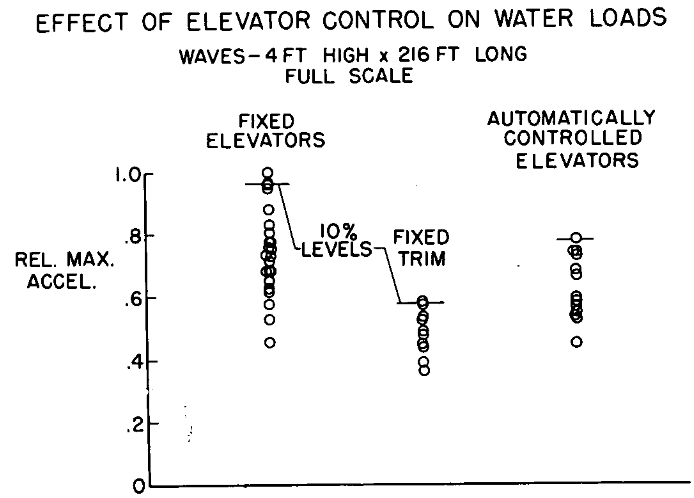

Figure 1

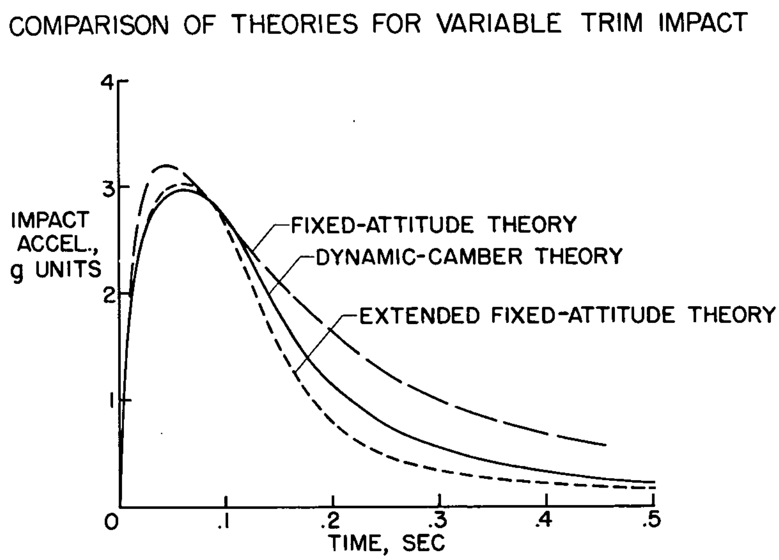

Figure 2

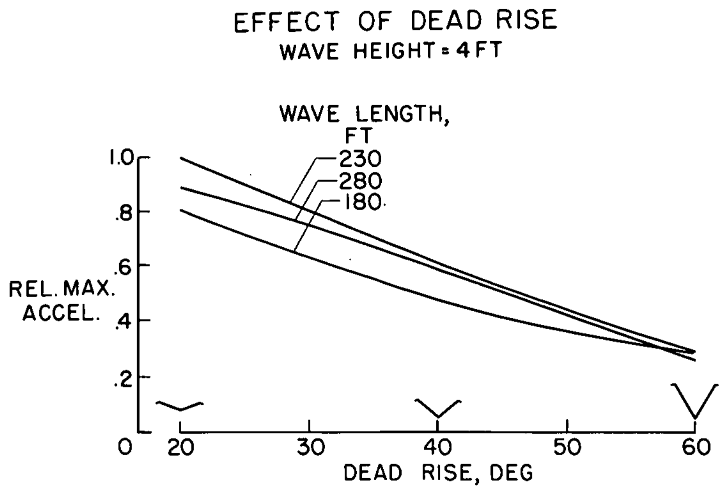

Figure 3

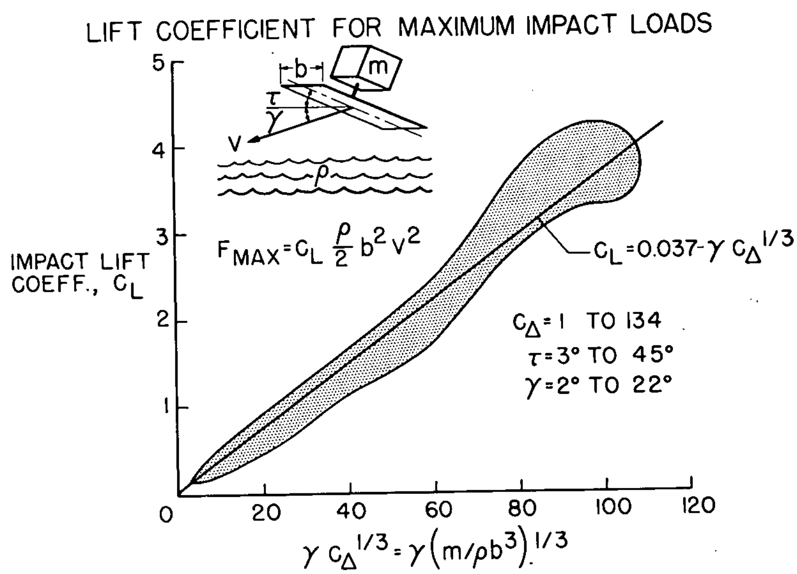

Figure 4

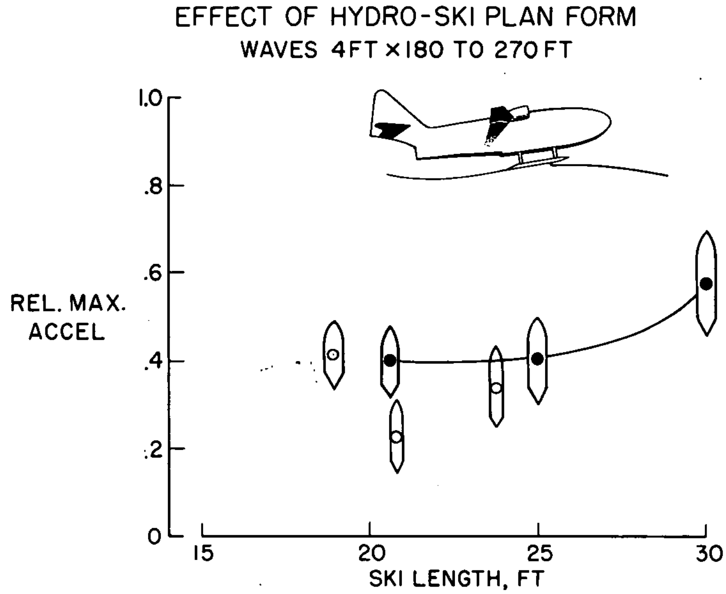

Figure 5

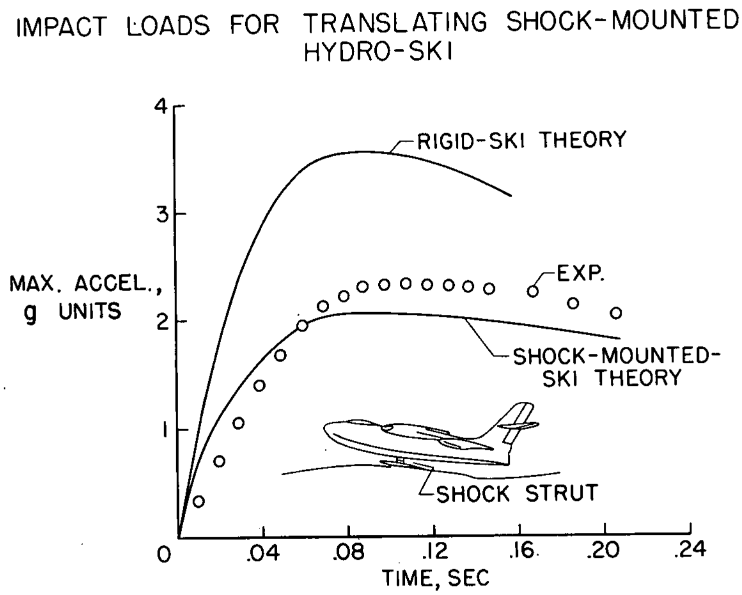

Figure 6

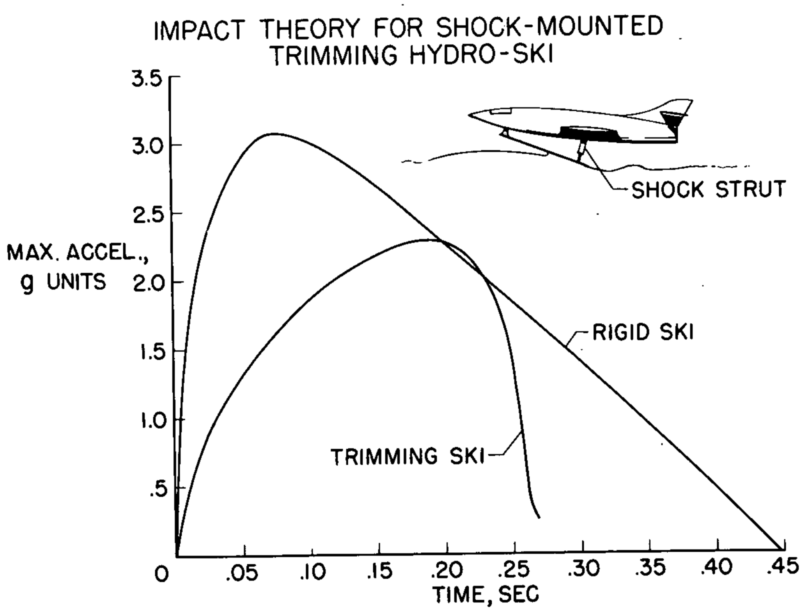

Figure 7

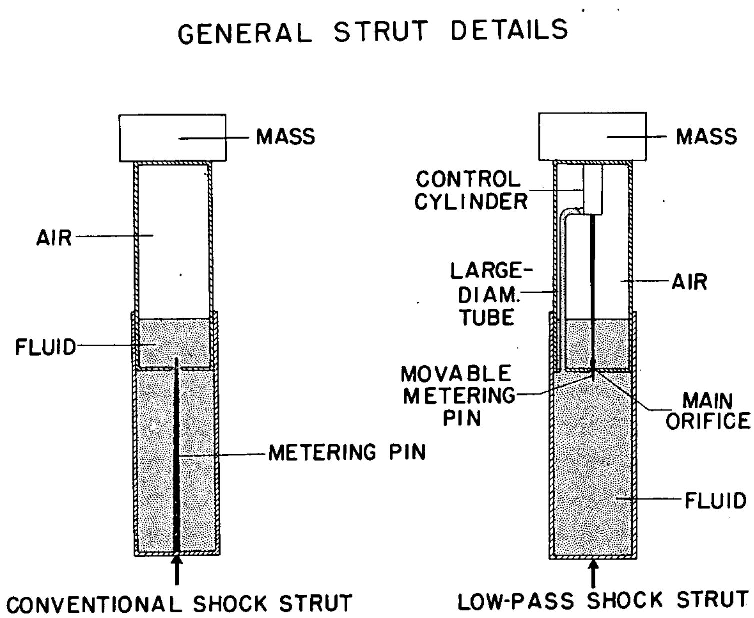

Figure 8

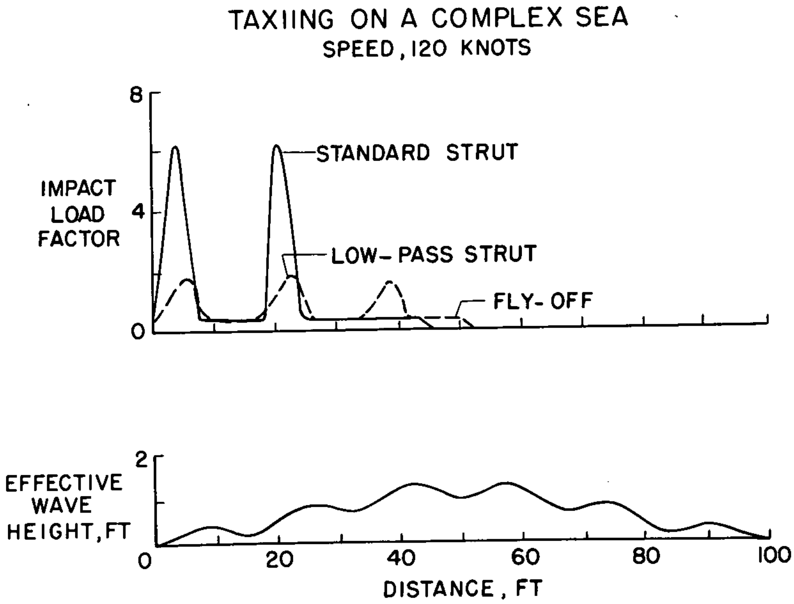
TAXIING ON A COMPLEX SEA
SPEED, 120 KNOTS
IMPACT LOAD FACTOR
8
4
0
STANDARD STRUT
LOW-PASS STRUT
FLY-OFF
EFFECTIVE WAVE HEIGHT, FT
2
0
20
40
60
80
100
DISTANCE, FT

Figure 9